Particle Based Modeling and Simulation of the Red Blood Cell Infected by Malaria -Mechanism of the Margination of the Infected Red Blood Cell-

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Abstract Motion and distribution of red blood cells in blood microvessels depend on vessel diameter, hematocrit (Hct), RBCs deformability and other factors. Migration of deformable red blood cells (RBCs) to the center of microvessels and away from the wall leads to the formation of cell-free layer (CFL). Few experiments or simulations considered the effects of motion and interaction of RBCs on CFL thickness. We employ a meshless (particle) method to model microvascular blood flow. An efficient parallel algorithm is developed for large-scale simulations of blood flow in microvessels. Using the developed method, we analyze the change in RBCs shape and RBCs distribution and also thickness of CFL in a variety of vessel sizes and Hct conditions. The results indicate that the CFL thickness increases when the vessel size increases or Hct decreases, which is in good agreement with previous experimental results. We also show change on RBCs shape and distribution for different microvessels diameter and Hct conditions.

Keywords: Malaria, Computational Fluid Dynamics, Particle Method, Red Blood Cell, Microcirculation, Mechanical Properties of Cell Membrane

1. Introduction

Blood plays a fundamental role in the transport and exchange of substances such as oxygen and nutrients, and also in the removal of the waste products such as urea and carbon dioxide. Blood flow in microcirculation is complicated because of the complex behavior of red blood cells (RBCs), which is dependent on their mechanical properties, their hydrodynamic interaction, microvascular geometry, and other factors. It results in interesting features, such as, generating the cell free layer (CFL) near the wall. Understanding of the CFL in microvessels is important because: I) substances are exchanged in this region; II) the CFL affects wall shear stress, hence the flow resistance; III) the CFL thickness influences the NO scavenging rate. However, the relationship between the behavior of RBCs and the CFL still remains unclear.

Experimental studies have difficulties in observing the motion and interaction of RBCs, particularly in high Hct conditions. Hence, researchers have tried to study the microvascular blood flow by means of numerical simulations. Several two-dimensional [1] and three-dimensional [2] computational models have recently been developed. Even though two-dimensional models capture qualitative behavior of RBCs, we should pay attention that actual RBCs behavior is inherently three-dimensional. A three-dimensional boundary integral method developed by H. Zhao [2] is limited to O(100) order of RBCs due to complexity and computational expense. We have developed a high performance parallel meshless (particle) method for large-scale simulation of blood flow in microvessels. In this paper, we apply our developed method to the analysis of the CFL and RBCs motion and distribution.

2. Methods

We have developed a numerical model based on a particle method [3] assuming that plasma

and cytoplasm are incompressible and Newtonian fluids. The governing equations are the continuity and Navier-Stokes equations. We use the moving particle semi-implicit (MPS) method [4] for discretizing the governing equations. A two-dimensional network of membrane particles connected by linear springs represents the membrane of an RBC. Stretching and bending forces are considered in the deformation of a thin membrane. These forces are substituted into the external force term of Navier-Stokes equation only for membrane particles [3].

In order to use parallel computer architectures, a domain decomposition method with a MPI library that accommodates data communication among processors is used. In the domain decomposition method, particles located at the overlap region of neighboring processors control the main overhead in the communications for parallel computing. We developed a method to minimize communications by reducing the overlap region.

To study the effects of vessel size and Hct on RBCs motion and CFL thickness, we simulate blood flow in straight circular channels with lengths from 50 to 120 μ m. Vessels with diameters range from 9.2 to 24 μ m, and a variety of Hct conditions from 20 to 45 are examined. Periodic boundary conditions are imposed at the inflow and outflow of the domain.

3. Results and discussion

Initially RBCs are placed randomly within a circular channel. We run the simulations for a long enough time to approach almost steady state. Figure 1 shows the snapshots of RBCs which are flowing in circular channels of three different diameters after reaching steady state. Our result shows that the shape of RBCs depends on the diameter, Hct and the radial position in microvessels. In the vessel with the similar diameter to RBCs, they have parachute shape (Fig. 1a). When the vessel diameter increases to 1.5 times larger than RBCs, the shape of RBCs depends on Hct. RBCs have elliptic shape in flow direction at low Hct (Fig. 1b), but at high Hct, parachute shape is also observed due to increase of the interaction between RBCs (Fig. 1c). As further increasing the diameter, the shape is parachute when they locate at the center of the vessel, whereas those near the cell free layer transient to an elliptic shape (Fig 1.d). To obtain the CFL thickness, we measure the outer edge of the RBC core. We divide the channel into small segments in the flow direction. In addition each segment is divided into several sub-segments in the angular direction. To determine the CFL thickness, we average the CFL over all segments. The CFL depends on the vessel diameter and Hct. A comparison of the simulated CFLs and those obtained in vivo experiments [5] is presented in Fig. 2. As shown in the figure, the CFL increases when the diameter increases or Hct decreases. The results obtained from our simulation agree well with corresponding experimental results.

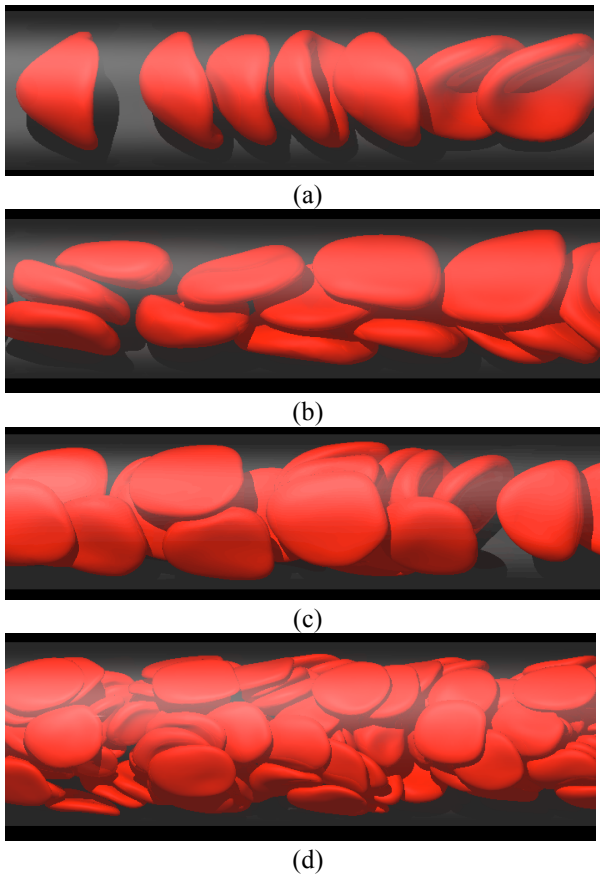

Fig. 1. Snapshots of numerical results: (a) D=9.2μm and Ht=26%; (b) D=12.8μm and Ht=19%; (c) D=12.8μm and Ht=30%; (d) D=24μm and Ht=34%).

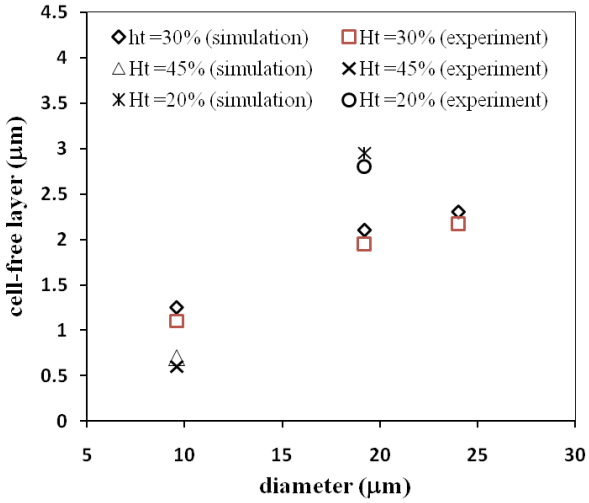

Fig. 2. CFL obtained from simulations compared with experimental data[5].

3. Conclusion

We have developed a novel 3-D parallel particle method for simulating micro-scale hemodynamics. Using the high speed-up parallel code, we successfully simulated blood flows in a variety of vessel sizes and Hct conditions. Our numerical results on the cell-free layer show good agreement with experimental results. The presented method can be used to investigate complex hemodynamics of microscale blood flows.

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